Generalized Source method for ultrafast rigorous modeling of pixelated DOEs with sub-wavelength feature size

T Kaempfe, A Tishchenko, W Eckstein, Y Jourlin

Generalized Source method for ultrafast rigorous modeling of pixelated DOEs with sub-wavelength feature size

T. Kaempfe[1], A. Tishchenko[1], W. Eckstein[2], Y. Jourlin[1]

[1]Lab Hubert Curien UMR CNRS 5516, Université Jean Monnet, 42000 Saint-Etienne, France
[2]Inst. of Appl. Physics, Friedrich Schiller University, Max-Wien-Platz 1, 07743 Jena, Germany
email: thomas.kampfe@univ-st-etienne.fr

Summary

Large, 2d-pixelated DOEs with subwavelength feature sizes are bringing the common rigorous calculation methods to their limits regarding memory usage and computation time. The generalized source method (GSM) breaks through this limitation, allowing for reasonable calculation times on a standard PC.

Introduction

There are various applications such as structured illumination, large aperture LED beam shaping or high efficiency image projection, which require large, pixelated diffractive optical elements (DOE) with feature sizes around and even below the wavelength. One especially sophisticated example are DOEs with effective medium based subwavelength pixels, capable of creating an optical function with multiple phase steps while retaining a binary height profile [1]. The optical response of such elements cannot be calculated by simple scalar approximations like the thin element approximation (TEA). On the other hand, established rigorous methods in the frequency domain (e.g. rigorous coupled wave analysis RCWA) are limited to very small element sizes if used in two lateral dimensions, whereas using the time domain (e.g. finite different time domain method FDTD) requires even larger computational efforts. Solutions in between TEA and rigorous methods exist, namely the FFT-BPM, providing a good compromise between precision and calculation time [2]. The GSM [3] is an ultrafast rigorous method where the fields and the optical structure are treated similarly to the well known RCWA, i.e. in Fourier space, where the number of used Fourier orders N corresponds to the precision of the representation of the structure and ultimately to the exactness of optical response. As mathematically derived in [3], the GSM allows to break the severe $O(N^2)$ limitation of known methods like RCWA, showing an O(n*log(n)) behaviour for calculation time and memory usage. However, contrary to RCWA it is an iterative method that needs to converge to the solution, and it needs a z-slicing of the structure. Therefore, there is a calculation overhead for small, binary structures and a low number of orders, where RCWA or modal methods excel. However, as shown in [4] for a simple checkerboard structure, this disadvantage is irrelevant for larger number of orders, where the O(n*log(n)) behaviour dominates. It is thus now possible that the GSM competes on with sophisticated scalar methods like FFT-BPM.
In this paper we present the application of the GSM to an effective medium DOE [3], allowing a fast and accurate simulation using up to 1024x1024 Fourier orders. Furthermore, parallelization of the code and the use of PC graphic-cards increase the calculation speed further allowing the rigorous calculation of subwavelength-DOEs with some hundred pixels per axis within minutes on a standard PC.

Discussion

The investigated structure is a diffractive pixelated optical element, based on binary, subwavelength, effective index pixels as described in [1]. It is based on an elementary cell of 20x20 pixels which is periodically repeated to create a positioning-independent, far-field computer generated hologram (CGH), creating a non-symmetric distribution of 9 arbitrarily positioned points. The calculation of the diffraction efficiency into all diffracted orders is used as criteria to compare methods. A reference is calculated by using RCWA with 64x64 orders (Fig. 1). The relative error between the methods is well below 0.1% when using 128 z-slices for the GSM, and can be further reduced by increasing this number further. The shown example corresponds already to the practical limit of RCWA on a standard PC in terms of calculation time (approx. 1h). Note that the graphic card accelerated GSM calculation time in this case is 160ms, which is already about 4 orders of magnitude faster than RCWA. The scalar approximation shown in [2] is still 2 orders of magnitude faster in this case even on a single x86 core but shows a lower precision. However, the GSM allows converging to a true rigorous solution without much additional effort by using more z-layers.

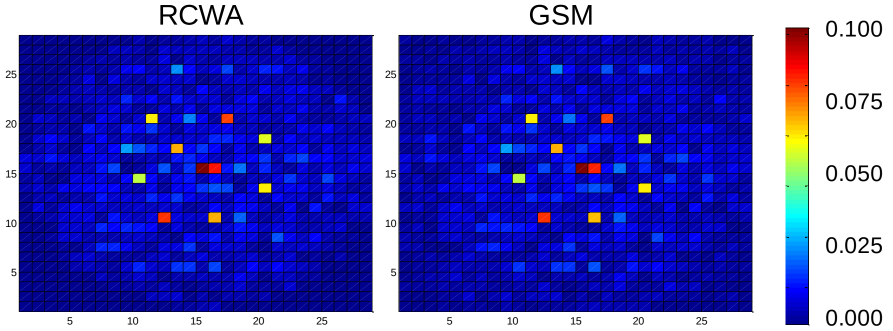

Fig.1. Diffraction efficiency into 9 arbitrarily positioned spots by an effective medium binary CGH, calculated by RCWA and GSM, relative to an incoming wave of amplitude = 1

Based on this confirmation of the validity of the GSM output the number of Fourier orders was increased to find the practical limit for this method. For 512 x 512 orders and 64 z-layers, the calculation time is about one minute, using about 30GB of memory, which can be considered a practical limit for a state of the art personal computer, impossible to be treated by RCWA or FDTD in a reasonable timeframe. An important further advantage of the GSM is its inherent z-slicing. Being sub-optimal for binary height-level structures, it will allow treating non-binary elements (e.g. rounded edges due to fabrication limits) without additional cost, whereas RCWA will have to introduce z-slicing increasing computation time and memory usage further.

Conclusions

The GSM as ultra-fast and memory sparing method, applied to subwavelength effective-index DOEs shows its potential for diffractive optics. It paves the way for the direct rigorous calculation and optimization of large, high spatial frequency elements. In the presentation we will quantitatively compare the methods and point out possible application examples where the use of GSM can enable significant progress.

References

[1] W. Freese, T.Kämpfe, E.-B. Kley and A. Tünnermann, Opt. Lett. 35, 676-678 (2010)
[2] W. Eckstein, E. Kley, and A. Tünnermann, Opt. Express 21, 12424-12433 (2013)
[3] A. A. Shcherbakov and A. V. Tishchenko, Quantum Electron. 40, 538 (2010)
[4] T. Kaempfe, A. Tishchenko, 8th EOS Meeting on Diffr. Opt., paper 4859, Delft, (2012)